# Electron-Pair Creation on the Uranium Nucleus

N. K. Sherman, W. F. Davidson, A. Nowak, M. Kosaki, and J. Roy
*Division of Physics, National Research Council, Ottawa, Canada K1A 0R6*

and

W. Delbianco and G. Kajrys
*Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Quebec H3C 3J7*
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From measurements of the total-absorption cross section for photon energies between 3 and 38 MeV we obtain values of the cross section for pair creation on the $^{238}$U nucleus. Theoretical values of the distorted-wave Born cross section for pair creation are available at 10 and 20 MeV. These, modified by radiative and screening corrections, are compared with $\sigma_\kappa$ obtained from the experiment. The agreement is within about 1% at 20 MeV. However, at 10 MeV the theoretical value is about 4% too small. The calculations likely can be improved by taking into account the finite size of the nucleus.

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In heavy elements absorption of photons whose energies exceed a few megaelectronvolts occurs mainly by creation of electron-positron pairs in the electric field of the nucleus. The cross section $\sigma_\kappa$ for nuclear pair creation is therefore of considerable practical importance. Yet even in the most recent tabulation,[1] calculated values of $\sigma_\kappa$ for large atomic number $Z$ are uncertain by about 1% for photon energies $\omega$ between 5 and 50 MeV. Øverbo, Mork, and Olsen[2] were able to calculate $\sigma_\kappa(\omega)$ exactly for $1 \leqslant Z \leqslant 100$ and $1.03 \leqslant \omega \leqslant 5$ MeV. Computation was too difficult for higher energies when $Z$ was large. On the other hand, Davies, Bethe, and Maximon[3] derived a form of $\sigma_\kappa(\omega)$ which is accurate at very high energies. However, between about 5 and 50 MeV the effects of screening and Coulomb distortion are significant and change rapidly with $\omega$. Hubbell *et al.* used improved screening corrections for $5 \leqslant \omega \leqslant 50$ MeV but their Coulomb corrections are semiempirical. Total-absorption measurements in our laboratory[4-7] on elements with $73 \leqslant Z \leqslant 83$ indicate that the tabulated values[1] of $\sigma_\kappa(\omega)$ are too small by 0.5% to 1% for $20 \leqslant \omega \leqslant 30$ MeV. Recently[8] Kosik and Wright, by dint of improved mathematical procedures and lengthy computations, obtained the pair cross section in distorted-wave Born approximation $\sigma_\kappa$ (DWBA) for uranium at 10 and 20 MeV with an uncertainty of about 0.25%. They assumed that the $^{238}$U nucleus is pointlike.

We have measured the absorption of pulsed 42-MeV bremsstrahlung by $^{\rm nat}$U and obtained experimental values of $\sigma_\kappa(\omega)$ which are uncertain by about 0.25%. We used a photon spectrometer[5-7] consisting of a liquid-deuterium target viewed by a neutron time-of-flight detector. The total cross section $\sigma(\omega)$ for photon absorption was obtained over the range $3 \leqslant \omega \leqslant 38$ MeV. The energy resolution $\Delta\omega/\omega$ varied from 0.2% to 3.3% over this range (the time resolution was 0.3 ns/m) and was 1.2% at 10 MeV and 2.1% at 20 MeV. The absorber consisted of two U disks of total thickness 13.935 mm and mass 530.860 g (density =18.759) whose end faces were parallel to within 12 $\mu$m, sandwiched between Al disks 2.54 mm thick. Heavy-element impurities did not exceed a few parts per million. The reference blank consisted of two identical Al disks. The data were collected during about 4000 cycles of interchange of absorber and blank, each cycle including an interchange with an empty cryogenic target. After dead-time correction and subtraction of background and empty-target contributions the cross sections are given by

$$\sigma(\omega) = (1/n)\ln F_0(\omega)/F(\omega) + \delta\sigma, \qquad (1)$$

where $F_0$ is the number of $^2$H$(\gamma,n)$ events in the time bin corresponding to $\omega$ without absorber, $F$ is the number of neutrons with absorber in the beam, and $n$ is the number of absorber atoms per unit area. The correction $\delta\sigma$ includes the effect of air displacement (0.003%), geometrical in-scattering (0.04%), and photon regeneration in the absorber. We have computed $\delta\sigma$ for the experimental geometry using simplified expressions for the electromagnetic cross sections and distributions contributing to secondary photon generation. Values are found in Table I.

The total cross section for photon absorption by an atom is

$$\sigma(\omega) = \sum_s \sigma_s(\omega) \quad (s = \kappa, N, \tau, \mathrm{pe}, \mathrm{coh}, \mathrm{incoh}), \qquad (2)$$

where the subscripts $s$ denote "nuclear pair," "photonuclear," "triplet," "photoelectric," "coherent scattering," and "incoherent scattering," respectively. Calculated values of what we will call $\sigma_{\rm other}$, the sum of cross sections for all atomic processes except nuclear pair creation,

$$\sigma_{\rm other}(\omega) = \sigma_{\rm coh} + \sigma_{\rm incoh} + \sigma_{\rm pe} + \sigma_\tau \qquad (3)$$

introduce uncertainties of not more than[1] 0.2% of

TABLE I. Measured total cross sections $\sigma$ give pair-creation cross sections $\sigma_\kappa$ for $^{238}$U after correction by $\delta\sigma$ for photon regeneration. Results of distorted-wave calculations,[a] multiplied by radiative[b] and screening[c] corrections, give $\sigma_\kappa$(theor), which are compared with the measurements.

| $\omega$ (MeV) | $\sigma$ (b) | $\sigma_N$ (b) | $\delta\sigma$ (b) | $\sigma_\kappa$ (b) | $\sigma_\kappa$(theor) (b) |
|---|---|---|---|---|---|
| 10.000 | 21.023 | 0.294 | +0.492 | 16.106 | 15.349 |
| ±0.129 | ±0.062 | ±0.032 | ±0.049 | ±0.092 | ±0.038 |
| 20.000 | 26.036 | +0.087 | +0.087 | 22.931 | 23.656 |
| ±0.388 | ±0.068 | ±0.009 | ±0.006 | ±0.068 | ±0.059 |

[a]At 10 MeV, $\sigma_\kappa(\mathrm{DWBA}) = 4.039\times10^{-2}$ MeV$^{-2}$ (±0.25%) (Ref. 8); at 20 MeV, $\sigma_\kappa(\mathrm{DWBA}) = 6.119\times10^{-2}$ MeV$^{-2}$ (±0.25%) (Ref. 8).
[b]$f_{\mathrm{rad}}(10\ \mathrm{MeV}) = 1.01223$; $f_{\mathrm{rad}}(20\ \mathrm{MeV}) = 1.01134$.
[c]At 10 MeV, $(1-R) = 0.9642$; at 20 MeV, $(1-R) = 0.9402$.

$\sigma(\omega)$ for all $Z$ and $\omega$ of interest here. Hence from measurements of $\sigma(\omega)$ and $\sigma_N(\omega)$ one can get

$$\sigma_\kappa(\omega) = \sigma(\omega) - \sigma_{\mathrm{other}}(\omega) - \sigma_N(\omega) \quad (4)$$

to accuracy of a fraction of a percent.

We report here values of $\sigma_\kappa$(10 MeV) and $\sigma_\kappa$(20 MeV) obtained from parabolic fits to our data. The solid lines in Fig. 1 represent these fits. Values of $\sigma_{\mathrm{other}}(\omega)$ were obtained from Eq. (3) by Lagrangian interpolation between tabulated values.[1] The average of two sets[9,10] of measurements of the total photoneutron cross section $\sigma_n$ was taken as a good approximation to $\sigma_N$:

$$\sigma_N(^{238}\mathrm{U}) \simeq \sigma_n(^{238}\mathrm{U}). \quad (5)$$

Double Lorentzians were fitted to the data sets—which ended at 18 MeV—and the 10- and 20-MeV values from the fits were averaged (see Table I). The two cross-section scales are respectively 11% larger[9] and smaller[10] than their average. This introduces a systematic uncertainty of 0.2% in our measured $\sigma_\kappa$ at 10 MeV and of 0.04% at 20 MeV. The statistical uncertainty is of the same order and has been included in our experimental uncertainty. Table I lists the experimental values of $\sigma_\kappa(\omega)$.

Using the relation

$$\sigma_\kappa = f_{\mathrm{rad}}(1-R)\sigma_\kappa(\mathrm{DWBA}) \quad (6)$$

where $f_{\mathrm{rad}}$ is the Mork-Olsen radiative correction and $1-R$ is a screening factor interpolated from the tables,[1] we obtained theoretical values $\sigma_\kappa$(theor) which are given in Table I.

The theoretical values are somewhat too small. The discrepancies (between the dashed lines and the lozenges in Fig. 1) are −4.7% at 10 MeV and −1.2% at 20 MeV. Values of $\sigma_\kappa$ calculated[1] with semiempirical Coulomb corrections and improved screening corrections, although much improved over earlier cal-

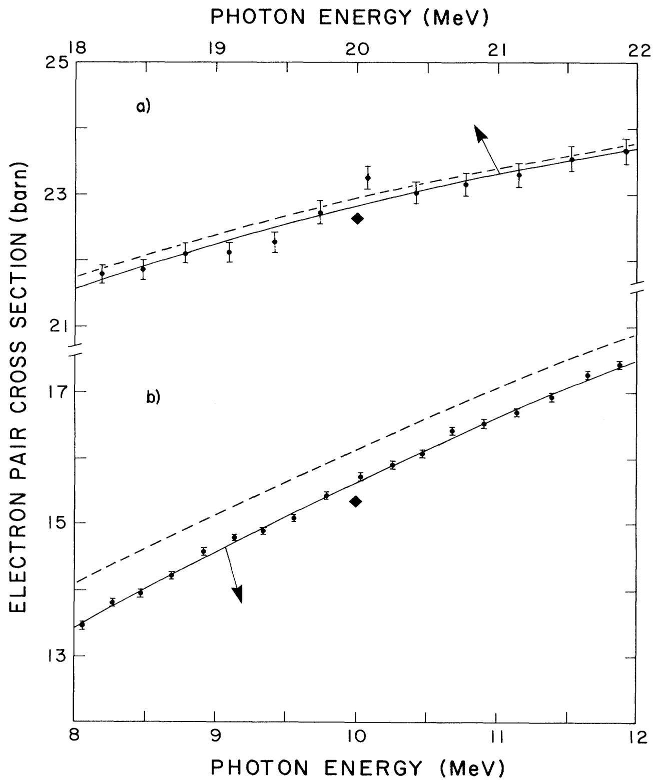


FIG. 1. (a) Measured electron pair-creation cross section $\sigma_\kappa$ of $^{\mathrm{nat}}$U (circles) as a function of photon energy $\omega$, for $18 \leq \omega \leq 22$ MeV, uncorrected for photon regeneration in the absorber. The solid line is a parabolic fit to the data over the wider range $17 \leq \omega \leq 28$ MeV. The lozenge is $\sigma_\kappa$(theor) for 20 MeV, derived from the theoretical DWBA cross section (Ref. 8). Corrections, photon regeneration being the dominant one, give the broken line. (b) Measured $\sigma_\kappa(\omega)$ of $^{\mathrm{nat}}$U for $8 \leq \omega \leq 12$ MeV. The solid line is a parabolic fit to the uncorrected data over the range $7.9 \leq \omega \leq 12.1$ MeV. The lozenge is $\sigma_\kappa$(theor) for 10 MeV derived from $\sigma_\kappa$ (DWBA). The broken line includes experimental corrections, mainly for photon regeneration.

culations, are also smaller than our uncorrected experimental values by about $-3.6\%$ and $-1.3\%$, respectively. These discrepancies are consistent with what our measurements on elements of smaller $Z$ showed.[4,6,7] The discrepancies are about 4 times the standard deviation of the measurements.

We note that in the theoretical calculations[8] a pointlike nucleus was assumed whereas the diameter of $^{238}$U is about one-quarter the wavelength of a 20-MeV photon. Kosik has argued that relaxing the pointlike assumption will increase $\sigma_\kappa$(DWBA) somewhat. A small increase in the theoretical value would indeed improve the already good agreement with our measurements at 20 MeV. There appears to be a real discrepancy at 10 MeV. A more refined calculation of $\sigma_\kappa$ is needed.

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